

INFLUENCE OF CURING CONDITIONS AND WIDTH
ON THE FRACTURE OF CONCRETE BEAMS

by

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B.S.. Chung-Hsing University, Taiwan, 1985

A MASTER'S THESIS

submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

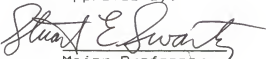
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1989

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TABLE OF CONTENTS

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ACKNOWLEDGEMENTS	iii
LIST OF TABLES	iv
LIST OF FIGURES	v
NOTATION	vii
CHAPTER 1 - INTRODUCTION	1
CHAPTER 2 - LITERATURE REVIEW	3
2.1 PROPOSED METHODS FOR FRACTURE TOUGHNESS AND ENERGY RELEASE RATE	3
2.2 EFFECTS OF CURING CONDITIONS ON THE FRACTURE OF CONCRETE	5
CHAPTER 3 - EXPERIMENTAL PROGRAM	7
3.1 TEST SPECIMENS	7
3.2 TESTING MACHINE AND SETUPS	8
3.3 TESTING PROCEDURE	11
3.3.1 TESTING OF PRECRACKED BEAMS	11
3.3.2 CYLINDER TESTS	13
3.4 TEST RESULTS AND COMMENTS	14
CHAPTER 4 - APPLIED METHODS AND EXPERIMENTAL RESULTS . .	36
4.1 METHODS OF CALCULATION FOR FRACTURE TOUGHNESS	36
4.1.1 GO / REFAI / SWARTZ (G/R/S) METHOD . .	36
4.1.2 JENQ / SHAH (J/S) METHOD	38
4.1.3 KARIHALOO / NALLATHAMBI (K/N) METHOD .	40
4.2 METHODS OF CALCULATION FOR ENERGY RELEASE RATE	42
4.2.1 J-INTEGRAL METHOD	42
4.2.2 ENERGY RELEASE METHOD	43
4.3 SUMMARY OF THE EXPERIMENTAL RESULTS	45

CHAPTER 5 - CONCLUSIONS	71
APPENDIX I, REFERENCES	73
APPENDIX II, LOAD VERSUS CMOD AND LPD DIAGRAMS FOR TYPICAL THREE-POINT BENDING SPECIMENS . . .	75

ACKNOWLEDGEMENTS

The author would like to express his appreciation to Dr. Stuart E. Swartz for his enlightenment and assistance during the period of research and preparation of this thesis.

Thanks are extended to Dr. Robert Snell, head of the Department of Civil Engineering, for his continual support during this research.

Also, the author is sincerely grateful to Mr. Liu and Mr. Luo, who volunteered to spend almost a summer period aiding the author's experimental work. In addition, thanks go to Mr. Ali Nikeen, Mr. Russell Gillespi, Miss Sze Ting Yap and Mr. Hoi Choong Siew for their expert suggestions that helped the author overcome numerous difficulties in the experiment.

Further and special gratitude is given to the author's families for their encouragement during the course of graduate study, especially the author's wife who provided a comfortable and supportive situation to finish this thesis.

LIST OF TABLES

Table 3.1	Mix Design	16
Table 3.2	Data of P_m Versus a_i/W for Oven-Dried Beams	17
Table 3.3	Summary of The Oven-Dried Cylinder Data . .	18
Table 3.4	Summary of The Air-Dried Cylinder Data . .	19
Table 3.5	Summary of The Saturated Cylinder Data . .	20
Table 4.1	K_{IC} Data by G/R/S Method for Oven-Dried Narrow Beams	47
Table 4.2	K_{IC} Data by G/R/S Method for Air-Dried Narrow Beams	48
Table 4.3	K_{IC} Data by G/R/S Method for Saturated Narrow Beams	49
Table 4.4	K_{IC} Data by G/R/S Method for Oven-Dried Wide Beams	50
Table 4.5	K_{IC} Data by G/R/S Method for Air-Dried Wide Beams	51
Table 4.6	K_{IC} Data by G/R/S Method for Saturated Wide Beams	52
Table 4.7	Average Value of Fracture Parameters . . .	53
Table 4.8	K_{IC} Data by Jenq/Shah Method for Narrow Beams	54
Table 4.9	K_{IC} Data by Jenq/Shah Method for Wide Beams	55
Table 4.10	K_{IC} Data by Karihaloo/Nallathambi Method for Narrow Beams	56
Table 4.11	K_{IC} Data by Karihaloo/Nallathambi Method for Wide Beams	57
Table 4.12	Average Values of Fracture Toughness Using Three Methods	58
Table 4.13	J_{IC} Values for Narrow Beams	59
Table 4.14	J_{IC} Values for Wide Beams	60

LIST OF FIGURES

Figure 3.1	Test Setup for 8" Deep Beams	21
Figure 3.2	A Set of Knife Edges for TPB Specimens	22
Figure 3.3	The LPD-Transducer Setup	23
Figure 3.4	Details of The Dye Reservoir	24
Figure 3.5	Specimen Precracking and Dye Application	25
Figure 3.6	The Typical Failure Surfaces for Each Group.	26
Figure 3.7	The Maximum Load Calibration Curves for Oven-Dried Beams	27
Figure 3.8	The Maximum Load Calibration Curves for Air-Dried Beams	28
Figure 3.9	The Maximum Load Calibration Curves for Saturated Beams	29
Figure 3.10	The Compliance Calibration Curve for Oven-Dried, Narrow Beams	30
Figure 3.11	The Compliance Calibration Curve for Oven-Dried, Wide Beams	31
Figure 3.12	The Compliance Calibration Curve for Air-Dried, Narrow Beams	32
Figure 3.13	The Compliance Calibration Curve for Air-Dried, Wide Beams	33
Figure 3.14	The Compliance Calibration Curve for Saturated, Narrow Beams	34
Figure 3.15	The Compliance Calibration Curve for Saturated, Wide Beams	35
Figure 4.1	K_{IC} vs. a_e/W for Narrow Beams, G/R/S METHOD	61
Figure 4.2	K_{IC} vs. a_e/W for Wide Beams, G/R/S METHOD.	62
Figure 4.3	K_{IC} vs. Moisture, G/R/S Method	63
Figure 4.4	U vs a_i/W for Oven-Dried Beams, J-Integral Method	64

Figure 4.5	U vs a_i/W for Air-Dried Beams, J-Integral Method	65
Figure 4.6	U vs a_i/W for Saturated Beams, J-Integral Method	66
Figure 4.7	P vs. LPD for The Energy Release Method	67
Figure 4.8	G_{IC} vs. a_e/W for Oven-Dried Beams	68
Figure 4.9	G_{IC} vs. a_e/W for Air-Dried Beams	69
Figure 4.10	G_{IC} vs. a_e/W for Saturated Beams	70

NOTATION

a, a_i, a_e	Crack Length, Initial Crack Length, Extended Crack Length
a_{oi}	Distance from The Crack "Mouth" to The Root of The "V-Shape" revealed by The Dye Penetrant
B	Beam Width
$CMOD$	Crack-Mouth-Opening Displacement
$CTOD_C$	Critical-Crack-Tip-Opening Displacement
E_c, E_t	Young's Modulus of Concrete in Compression and Tension
f_c'	Uniaxial Compressive Strength of Concrete
f_{tw}', f_{tn}'	Splitting Tensile Strength of Concrete, Using Wide Strip, Narrow Strip Between Cylinder and Testing Surfaces
f_r'	Modulus of Rupture
g	Maximum Aggregate Size
G_{IC}	Energy Release Rate
J	J-Integral Value for Mode I Fracture
J_{IC}	Energy Release Rate by J-Integral Method
K_{IC}	Opening Mode Fracture Toughness or Critical Stress Intensity Factor
LPD	Load-Point Displacement
M	Moment Due to Three-Point Bending
N	Number of Segments by The Energy Release Method
P, P_m	Applied Load, Maximum Load or Load Capacity
S	Beam Span
r, θ	Polar Coordinates
U, U_t	Total Elastic Energy
V	Potential Energy

v	Measured Load-Point-Displacement
W	Beam Depth
w	Moisture Content, %
ϕ	Williams' Stress Function

CHAPTER 1

Introduction

In the literature, to date, much research has been reported dealing with curing conditions on the subsequent strength of concrete; however, few reports mention this effect on the fracture properties of concrete. Until now, most of the fracture mechanics tests have dealt only with either air-dried specimens or saturated specimens. However, since several standard test methods have been proposed, the investigation of the influence of curing conditions on cracking and fracture of concrete can be conducted.

The research presented here evaluates the influences of size and curing conditions on the fracture of plain concrete using the methods of fracture mechanics. The analysis utilized herein is based on several proposed methods for the determination of fracture toughness and energy release rate.

The method developed by Go, Refai and Swartz (1, 2, 3) to determine the opening-mode fracture toughness K_{IC} was utilized; in addition, the energy release rate G_{IC} based on linear elastic fracture mechanics (LEFM) and using the calculated K_{IC} was carried out. Two other energy release rates based on the J-Integral method (2,4) and the method proposed by Refai (2, 5) were obtained to compare with the G_{IC} . Additionally, some specific beams with crack depth/beam depth ratio a_i/W of about 0.4 or 0.5 were used to

determine K_{IC} methods proposed by Jenq/Shah (6) and Nallathambi/Karihaloo (7). A detailed description of these methods is found in Chapter 4.

Two series of 36 beams each were made. Each beam series was classified into three groups for three specific curing conditions (i.e., oven-dried, air-dried and saturated). The three-point bending test was used throughout the experiment. The test specimens and test setups as well as the curing conditions are mentioned in Chapter 3.

Each beam was precracked and a dye technique was used (1, 2, 3) to reveal the crack shape of each precracked beam such that the crack growth could be predicted. As a result, the maximum load calibration method and the modified compliance calibration method (2, 3) could be applied to estimate any extended or effective crack length a_e from which the fracture toughness could be found through the three proposed formulas. In general, the results obtained from the three proposed methods are in agreement. The experimental and analytical results are shown in Chapter 4 and the conclusions and summaries are presented in Chapter 5.

CHAPTER 2

Literature Review

2.1 Proposed Methods for Fracture Toughness and Energy Release Rate

Since 1961, when Kaplan (8) first applied the concept of fracture mechanics to concrete, a great deal of research has been conducted to evaluate the fracture parameters for this material. It is believed that the stress intensity factor K should be a material property based on linear elastic fracture mechanics (LEFM). In opening mode (Mode I) fracture, a stress intensity factor K_I can be found which is related to the stress state at the crack tip. The critical value of this is associated with unstable crack growth and is referred to as the fracture toughness K_{IC} . This has been proposed as a fracture criterion of the material (1, 2, 3, 6, 7).

In the past years, several test methods using a three-point bending setup to evaluate the fracture toughness in the opening mode were developed and suggested to be standard methods. Jenq and Shah (6) used a direct method to calculate two size independent fracture parameters, i.e., critical stress intensity factor K_{IC} and critical crack tip opening displacement $CTOD_c$. This was done from the experimental results using single-edge-notched beams. One advantage of this method is that the post-peak (strain softening) constitutive law is not needed.

Nallathambi and Karihaloo (7) used an effective crack model to propose another direct method which is similar to the Jenq/Shah method. The fracture toughness K_{IC} and energy release rate G_{IC} were shown to be two parameters independent of the specimen dimensions. A regression formula based on a series of tests was developed to determine the extended crack length directly, so that no feedback control is required.

Go and Swartz (1) presented a modified compliance calibration method using a dye technique to reveal the crack surface of a precracked beam so as to obtain a nominal crack length, created by dividing the dyed area by the width of the beam. An effective crack length a_e , corresponding to the instability point, could be found using a compliance calculation technique. The mode I fracture toughness K_{IC} was estimated from a formula, derived from using the least squares method and based on the bending analogy analysis (9). The energy release rate G_{IC} was determined using the LEFM relation without considering Poisson's ratio. On the basis of this work, Refai (2, 3) refined the method by using a maximum load calibration technique to estimate the extended crack length in a consistent way. In addition, the results agreed with other proposed methods (6, 7).

Some other research based on the energy principle was developed to determine the energy release rate for concrete. Rice (10) developed the J-integral method which is applicable for either a linearly elastic or nonlinear

material. A parameter J_{IC} is considered to be the energy release rate with exactly the same meaning and value as G_{IC} if linear elastic fracture mechanics is valid. The only restriction when using this method is that unloading is not permitted. Based on this concept, Go presented a formula (2, 4) considering the roughness of the crack surface and determining the energy release rate directly by change in energy versus change in crack extension. The slope of the best line that fits the data gives the energy release rate, J_{IC} .

Refai also derived an energy release method (2, 5), using only the fundamental definition of energy release rate, G_{IC} . A practical formula was recommended for the calculation of the energy release rate G_{IC} from the load versus load-point-displacement (P-LPD) diagram. This is not necessarily an LEFM parameter. The maximum load versus compliance curve as well as the regression equation of maximum load versus crack length are required in this method.

2.2 Effects of Curing Conditions on The Fracture of Concrete

Up to now, rarely has research been presented relating to the investigation of the influence of curing conditions on the fracture properties of concrete, even though a great deal of similar work on the strength of concrete was reported in the literature.

Recently, Hordijk and Reinhart (11) presented results on tensile response and strength as influenced by curing conditions. Bazant and Prat (12) also have reported test results, using three-point bend and eccentric compression specimens, and evaluating the effects of temperature and humidity or water content on the Mode I fracture energy of concrete. The temperature effect was determined both for concrete predried in an oven and for saturated concrete. By interpolation, an approximate formula for the effect of moisture content on fracture energy was also obtained. It was found that the fracture energy of concrete significantly depends on temperature and that the effect of moisture content is small at room temperature but large at temperature close to 100°C (212°F). In addition, the size effect law (13) was verified to be applicable based on various specimens with similar geometry.

CHAPTER 3

Experimental Program

3.1 Test specimens

Two series of plain concrete beams were made in this experiment with the dimensions shown as follows:

Series D: width, $B = 3$ in. (76 mm)
depth, $W = 8$ in. (203 mm)
span, $S = 32$ in. (813 mm)
length, $L = 34$ in. (864 mm)

Series E: width, $B = 6$ in. (152 mm)
depth, $W = 8$ in. (203 mm)
span, $S = 32$ in. (813 mm)
length, $L = 34$ in. (864 mm)

Each series included 36 beams which were constructed using the mix design given in Table 3.1. In each series, the beam specimens were divided into three groups of 12, and each group was exposed to three specific curing conditions. The curing conditions were: one day in the plywood casting mold with a plastic sheet over the exposed surface and 30 days in a 100% humidity curing room, then

- a. Oven-dried: 60 days in an oven at 77°C (171°F),
- b. air-dried: 60 days in the laboratory environment,
- c. saturated: 60 additional days in the curing room.

Consequently, a total of six different groups were arranged, based on size (width) and curing condition. For convenience, the capital letters D and E are used to represent the narrow

beams of 3 in. width and the wide beams of 6 in. width, respectively; hence, the beam number as well as each pertaining group could be set up according to the following:

	Oven-dried	Air-dried	Saturated
Narrow	D1-D12	D13-D24	D25-D36
Wide	E1-E12	E13-E24	E25-E36

In addition, at least four cylinders of 3"x 6" (76 mm x 152 mm) were made in each batch to obtain the appropriate properties of concrete. Two of the cylinders were taken for compressive strength tests; one was for the measurement of the moisture content of concrete and the rest were used for the splitting test to obtain approximate tensile strength.

3.2 Testing Machine And Setups

An electro-hydraulic, closed-loop, materials testing system (MTS) machine was used for all of the beam tests. For some practical reason, the configuration utilized in this research was designed as an upside-down, three-point bend setup as shown schematically in Figure 3.1. At the terminals (plotters) of the machine, the crack-mouth-opening displacement (CMOD) and the load-point displacement (LPD) were simultaneously monitored through two transducers with a maximum sensitivity of ± 0.002 in (0.0508 mm) per 10 volt full scale output. A set of knife edges as shown in Fig. 3.2 was bonded to the beam and used to contact with the CMOD transducer at the notch. Also, the relative LPD was measured by attaching the gage to the knife-edge-spring

setup which was attached on the side of the square steel plate that fitted firmly around the moving piston. This is shown in Fig. 3.3.

In MTS, there are three available control modes, i.e., load control, strain control and stroke control. Under load control, the span (amplitude) responds to the amount of load as the primary feedback with a constant load rate using the ramp function. This control was used when loading the specimens to failure. When using strain control, the span responds to the displacement of the CMOD transducer as the primary feedback, which makes it possible to crack the beam to a desired depth with less danger of premature failure since the rate of CMOD is more controllable than the load rate. The stroke control, using the displacement of the loading head as its primary feedback, was applied only for the work of warm-up before testing.

To get the traces of the load versus CMOD as well as LPD, appropriate scale settings on the plotters should be selected. The plotters used were each MTS 431.13A-02 (Type 200 Control Module). A summary of X (load) and Y (displacement) axis scale setting follows (cm refers to plotted length):

X-axis Metric Setting

Ranges using calib. setting:

0.5% per cm	= 0.05 v/cm
1.0% per cm	= 0.10 v/cm
2.5% per cm	= 0.25 v/cm
5.0% per cm	= 0.50 v/cm
10.0% per cm	= 1.00 v/cm

CMOD - Range 2, $\pm 1 \times 10^{-2}$ in./10 v = $\pm 1 \times 10^{-3}$ in./v

0.5%: 1 cm = 5.0×10^{-5} in.

1.0%: 1 cm = 1.0×10^{-4} in.

2.5%: 1 cm = 2.5×10^{-4} in.

5.0%: 1 cm = 5.0×10^{-4} in.

CMOD - Range 1, $\pm 2 \times 10^{-2}$ in./10 v = $\pm 2 \times 10^{-3}$ in./v

0.5%: 1 cm = 1×10^{-4} in.

1.0%: 1 cm = 2×10^{-4} in.

2.5%: 1 cm = 5×10^{-4} in.

5.0%: 1 cm = 1×10^{-3} in.

LPD - Range 2, $\pm 9.72 \times 10^{-4}$ in./v

0.5%: 1 cm = 4.86×10^{-5} in.

1.0%: 1 cm = 9.72×10^{-5} in.

2.5%: 1 cm = 2.43×10^{-4} in.

5.0%: 1 cm = 4.86×10^{-4} in.

LPD - Range 1, $\pm 19.08 \times 10^{-4}$ in./v

0.5%: 1 cm = 9.54×10^{-5} in.

1.0%: 1 cm = 19.08×10^{-5} in.

2.5%: 1 cm = 4.77×10^{-4} in.

5.0%: 1 cm = 9.54×10^{-4} in.

Y-axis Metric Setting:

Ranges using calib. setting:

0.5% per cm = 0.05 v/cm

1.0% per cm = 0.10 v/cm

2.5% per cm = 0.25 v/cm

5.0% per cm = 0.50 v/cm

10.0% per cm = 1.00 v/cm

CMOD and LPD - All Ranges 1.0 v = 1000 lb.

Using load cell with $\times 10$

0.5%: 1 cm = 50 lb.

1.0%: 1 cm = 100 lb.

2.5%: 1 cm = 250 lb.

5.0%: 1 cm = 500 lb.

Several load versus CMOD and LPD plots of typical beams are shown in Appendix II.

3.3 Testing Procedure

3.3.1 Testing of Precracked Beams

The maximum load calibration method (2, 3), which relates the load capacity of a concrete beam to the corresponding initial crack length as well as the initial compliance, was used for each precracked beam based on the three-point bend test. It is natural that the load capacity should decrease as the crack grows. As a result, a relationship could be found to predict other crack lengths.

Before precracking each beam, some preparation was needed. On the same day after casting, the specimens were removed from the curing room (i.e., the 30th day), and each beam was notched by a diamond saw at midspan to a depth of about 0.8" (20.3 mm). This was done to assure that the crack would start at midspan. At a week before the test, two aluminum sheets of 4"x 7.5" (102 mm x 191 mm) were attached using silicon rubber to either side of the specimen near the midspan to form a reservoir, as shown in Fig. 3.4.

Through the three-point bending test with strain control, each beam was loaded to a certain postpeak load on the softening branch, and then unloaded. At the same time, a plot of load versus CMOD was obtained. After this procedure, the dye (i.e., "Vanish", a product of the Drackett Products Company) was added into the reservoir, and

the beam specimen underwent a load-cycling procedure with a peak-load about one third of the load capacity, which lasted about 30 minutes. When the dye and the aluminum sheets were removed and the specimen was dried, a precracked beam was completed. This procedure is illustrated in Fig. 3.5 and referred to in Ref. 5. In Fig. 3.5(a), it is noted that the load with a scale of $Y = 2.5$ was removed after softening to a level about one half the peak load and the process restarted with $Y = 1.0$ (scale change only for convenience). Note that the crack closure effects (14) can be observed from the change of the initial slope in the restarted plot ($Y = 1.0$). Referring to the left curve in Fig. 3.5(b), a load-displacement plot is made for reference purposes. The load is then removed.

Once prepared (precracked) for testing, the beam was reloaded to failure, and the traces of P-CMOD and P-LPD were plotted at the same time. If a test to determine K_{IC} by the Jenq/Shah method (6) is required, for instance, it will be necessary to remove the load at $0.95 P_m$ on the unload curve and then reload to obtain the compliance at that load. This can be done even if load control is used.

After the beam was broken, the area of dyed surface was measured such that the initial, equivalent crack length could be calculated as:

$$a_i = \frac{\text{area of dyed surface}}{B}$$

The crack front surfaces for representative beams from each group with a_i/W about 0.5 are shown in Fig. 3.6.

For each group, the first eight beam specimens were used to obtain the relationships of the maximum load capacity P_m versus the initial crack length a_i , as well as versus the initial stiffness (i.e., the inverse of the initial compliance C_i) using the least squares method. Then the rest were tested based on the determined curve or equation to obtain a desired crack length by applying the load to a certain point. The calibration curves of P_m-a_i/W for different widths and curing conditions can be found in Figs. 3.7 to 3.9 and the compliance curves of P_m-1/C_i for each group are shown in Figs. 3.10 to 3.15. Unfortunately, for both of the calibration curves of P_m-a_i/W for oven-dried beams, it was unsuccessful to apply the least squares method; however, a simple table could be set up instead by fitting the curves by eye. A table demonstrating these two curves is shown in Table 3.2.

3.3.2 Cylinder Tests

All of the properties of the concrete specimens were measured from the cylinder tests. The compressive strength f_c' , splitting-tensile strength f_t' , and the secant modulus of elasticity at $0.45 f_c'$ were obtained from the tests in the conventional way. An additional experiment was made to measure the water content of the concrete specimens in different curing conditions. When the concrete specimen was

removed from the specific curing environment, one of the cylinders of the same batch as the specimen was taken out and weighed. After weighing, the cylinder was placed in an oven at a constant temperature of 105°C (221°F) 7 days (168 hrs) to drive the free water out and then the dried cylinder was weighed. The period of drying the cylinder was felt to be long enough and agreed with the work by Huang, Jiang and Best (15). The moisture content was therefore determined by dividing the free water by the dried weight of the cylinder. A summary of those results is shown in Tables 3.3 to 3.5.

3.4 Test Results and Comments

From Fig. 3.6, it is seen that the "side lips" are indeed a surface effect as the wider beams (series E) have a relatively flat crack front in the middle portion of the section in addition to the lips. Note that the oven-dried beams in both series (D1-D12, E1-E12) had connected and unconnected cracks near the surface of sufficient size to allow dye to penetrate in long, narrow zones, such as shown for beam D11. This is in contradistinction to a surface-penetration of 2-3 mm which occurred in most of the beams.

Because the "side lips" are a local phenomenon, it should be expected that the wider the beam, the closer the average crack depth a_i as determined here will be to the actual depth at the center "plateau". Hence, it may be expected that for a given load P_m , normalized to the beam width, the wider beams will have lower a_i than narrower

beams. This is indeed the case as is shown in Fig. 3.9 which displays a_i/W versus P_m for narrow (D) and wide (E) beams. If the curve for the wide beams is normalized to that for the narrow beams by dividing by two, it is seen that for the same load P_m the crack length of a wide beam is less than that of a narrow beam. For instance, compare the crack length of the wide beam at load 8 kN to that of the narrow beam at load 4 kN.

The tensile strength in Table 3.3 to 3.5 has two values which were obtained by using two different sizes of wood strips for the splitting test. Although the standard method of splitting test has been presented and applied for a long time, no manual or study mentioned details about the dimensions of wood strips for various sizes of cylinders. The standard width of the wood strip for the 6" x 12" (152 mm x 305 mm) cylinder specimen is 1 in. (25.4 mm). In the study, the width of the wood strip used was 1 in. and 0.5 in., and the corresponding tensile strengths of the concrete were denoted as f_{tw}' and f_{tn}' , respectively. The tensile strengths tested using the wide strips were about 50% higher than those with narrow strips. It is felt more reasonable to use the narrow strip, proportioned to the standard size; however, the value obtained from using the wide strip seems closer to the value of modulus of rupture f_r' , which is in an approximate range of 8 to 12 $\sqrt{f_c'}$ in accordance to Reference (16).

Table 3.1 Mix Design

Water/Cement	0.49
Cement Type	I
S.G. Sand	2.65
S.G. Aggregate	2.56
S.G. Cement	3.15
% Sand by Weight	32.68
% Aggregate by Weight	47.46
% Cement by Weight	13.24
% Water by Weight	6.05
% Superplasticizer	0.44
Maximum aggregate size	0.75 in. (19 mm)

	lb/ft ³ (kg/m ³)	ft ³ (m ³)

Aggregate	71.05 (1138.0)	0.4448
Sand	48.92 (783.7)	0.2958
Cement	19.82 (317.5)	0.1008
Water	9.05 (145.0)	0.1450
Superplasticizer (S.G. = 2.0)	0.66 (10.6)	0.0053
Air		0.0083
Slump	1.00 in (25.4 mm)	

Unit Weight of Concrete = 149.5 lb/ft³ (2395 kg/m³)

Table 3.2 Data of P_m Versus a_i/W for Oven-Dried Beams

P_m , kN (lb)	a_i / W	
	(a) Narrow Beams	(b) Wide Beams
0.0 (0)	1.000	1.000
0.5 (112)	0.702	0.783
1.0 (225)	0.575	0.655
1.5 (337)	0.495	0.555
2.0 (449)	0.435	0.489
2.5 (562)	0.388	0.444
3.0 (674)	0.353	0.407
3.5 (787)	0.322	0.376
4.0 (899)	0.298	0.347
4.5 (1011)	0.278	0.325
5.0 (1124)	0.260	0.305
5.5 (1236)	0.246	0.288
6.0 (1348)	0.233	0.273
6.5 (1461)	0.224	0.260
7.0 (1573)	0.214	0.248
7.5 (1685)	0.206	0.239
8.0 (1798)	0.200	0.231
8.5 (1910)	0.194	0.224
9.0 (2022)	0.189	0.218
9.5 (2135)	0.185	0.212
10.0 (2247)	0.181	0.206
10.5 (2360)	0.178	0.200
11.0 (2472)	0.175	0.196

Note: This table refers to Fig. 3.7.

Table 3.3 Summary of The Oven-Dried Cylinder Data

	f_c^1 , psi MPa	f_{tw}^1 , psi MPa	f_{tn}^1 , psi MPa	E_c , psi $\times 10^6$ GPa	ϵ_o , in/in, $\times 10^{-3}$ m/m, $\times 10^{-3}$	w, %
	7397 51.0	799 5.51	552 3.80	4.27 29.4	2.74	0.13
	8703 60.0	955 6.58	630 4.34	5.08 35.0	2.22	0.10
	9213 63.5	955 6.58	679 4.68	4.95 34.1	2.81	0.18
	7595 52.3	771 5.31	584 4.02	4.17 28.7	2.90	0.12
	6719 46.3	821 5.66	531 3.66	4.77 32.9	2.15	0.06
	7793 53.7	884 5.82	573 3.95	4.51 31.1	2.21	0.19
	7166 49.4	806 5.55	552 3.80	4.98 34.3	2.02	0.06
	8251 56.8	1016 7.00	601 4.13	5.06 34.9	1.81	0.12
	8581 59.1	828 5.70	523 3.60	5.09 35.1	2.22	0.06
	9250 63.7	817 5.63	587 4.04	4.76 32.8	2.26	0.12
N	29	10	10	10	10	10
Average	8067 55.6	865 5.96	581 4.00	4.76 32.8	2.33	0.11
Std Dev.	824 5.68	79 0.54	45 0.31	0.32 2.2	0.36	0.04
C. V.	10.2%	9.1%	7.7%	6.8%	15.5%	38.6%

¹ Average for each batch

Table 3.4 Summary of The Air-Dried Cylinder Data

	f_c' , psi MPa	f_{tw}' , psi MPa	f_{tn}' , psi MPa	E_c , psi $\times 10^6$ GPa	ϵ_0 , in/in, $\times 10^{-3}$ m/m, $\times 10^{-3}$	w, %
	8289 57.1	856 5.90	693 4.77	5.79 39.9	2.15	2.48
	9095 62.7	835 5.75	559 3.85	5.34 36.8	2.18	2.77
	9703 66.9	877 6.04	630 4.34	5.54 38.2	2.30	2.98
	9137 63.0	1004 6.92	707 4.87	5.38 37.1	2.10	2.32
	9887 68.1	1174 8.09	608 4.19	5.38 37.1	2.26	2.39
	10057 69.3	1125 7.75	622 4.29	5.42 37.3	2.14	2.43
	10254 70.7	1047 7.21	693 4.77	6.64 45.8	1.73	2.27
	9463 65.2	1075 7.41	736 5.07	5.53 38.1	2.04	2.43
	9887 68.1	923 6.36	736 5.07	6.34 43.7	2.22	2.82
	10099 69.9	1004 6.92	686 4.73	6.55 45.1	2.02	2.31
N	20	10	10	10	10	10
Average	9587 66.1	992 6.83	667 4.60	5.79 39.9	2.11	2.52
Std Dev.	572 3.94	111 0.76	56 0.39	0.49 3.38	0.16	0.23
C.V.	6.0%	11.2%	8.4%	8.5%	7.6%	9.3%

¹ average for each batch

Table 3.5 Summary of The Saturated Cylinder Data

	f_c' , psi MPa	f_{tw}' , psi MPa	f_{tn}' , psi MPa	E_c , psi $\times 10^6$ GPa	ϵ_0 , in/in, $\times 10^{-3}$ m/m, $\times 10^{-3}$	w, %
	8769 60.4	905 6.24	619 4.26	5.06 34.9	1.73	3.78
	8161 56.2	983 6.77	559 3.85	5.40 37.2	1.98	3.88
	8359 57.6	898 6.81	615 4.24	5.54 38.2	1.80	3.27
	8529 58.8	912 6.28	559 3.85	5.80 40.0	2.17	4.03
	8670 59.7	1146 7.90	644 4.44	5.75 39.6	1.78	3.92
	7780 53.6	934 6.44	729 5.02	5.37 37.0	2.20	3.71
	8628 59.4	994 6.85	707 4.87	5.11 35.2	2.03	3.81
	8529 58.8	856 5.90	481 3.31	6.15 42.4	2.01	3.86
	8755 60.3	1082 7.45	601 4.14	5.82 40.1	1.96	3.61
	9151 63.1	927 6.39	644 4.44	5.61 38.7	2.13	3.62
N	26	10	10	10	10	10
Average	8529 58.8	964 6.64	616 4.24	5.56 38.3	1.98	3.75
Std Dev.	327 2.25	85 0.59	69 0.48	0.32 2.20	0.17	0.20
C.V.	3.8%	8.8%	11.2%	5.8%	9.6%	5.3%

¹ average for each batch

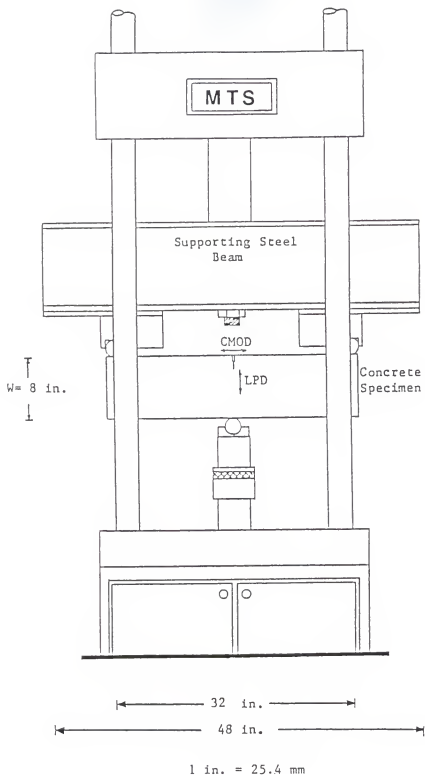
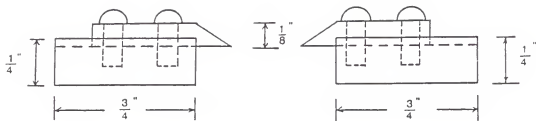
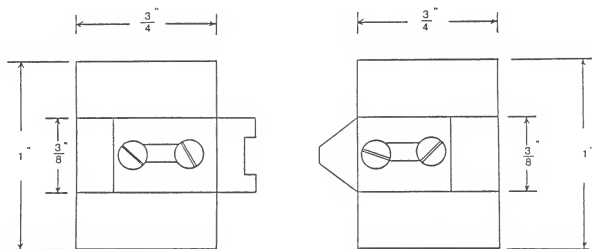


Fig. 3.1 Test Setup for 8" Deep Beams (2)



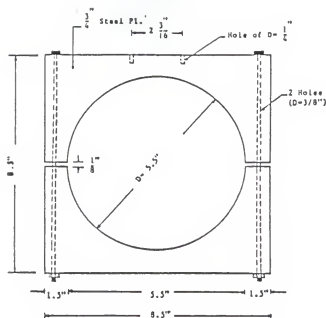
Side view



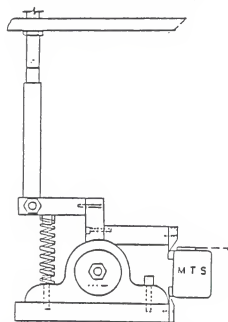
Plan view

1 in. = 25.4 mm

Fig. 3.2 A Set of Knife Edges for TPB Specimens



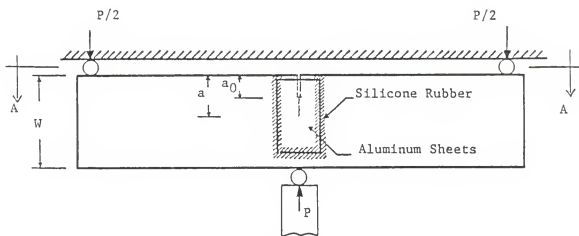
(a) Square Plate with a Circular Hole
(Attached to The Piston)



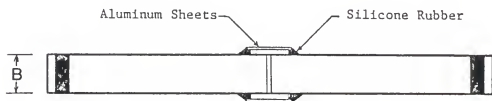
(b) Transducer-Supporting Device
(Attached to The Plate)

1 in. = 25.4 mm

Fig. 3.3 The LPD-Transducer Setup (2)

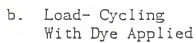
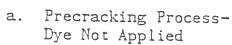


Elevation View



Section A-A View

Fig. 3.4 Details of The Dye Reservoir



25

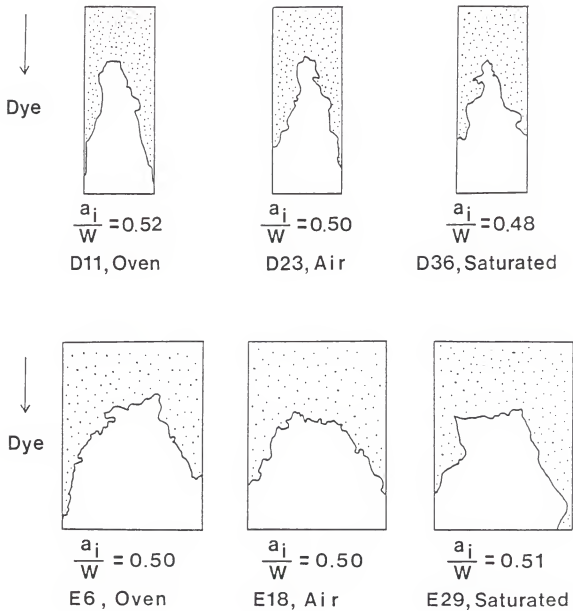


Fig. 3.6 The Typical Failure Surfaces for Each Group

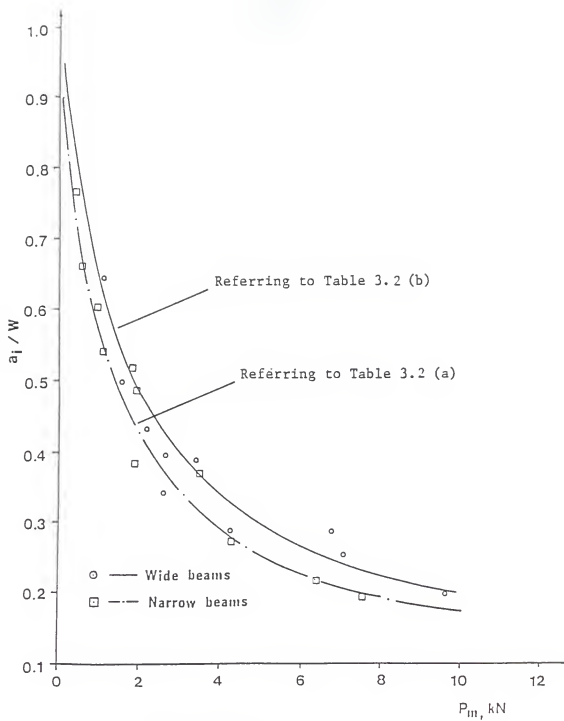


Fig. 3.7 The Maximum Load Calibration Curves
for Oven-Dried Beams

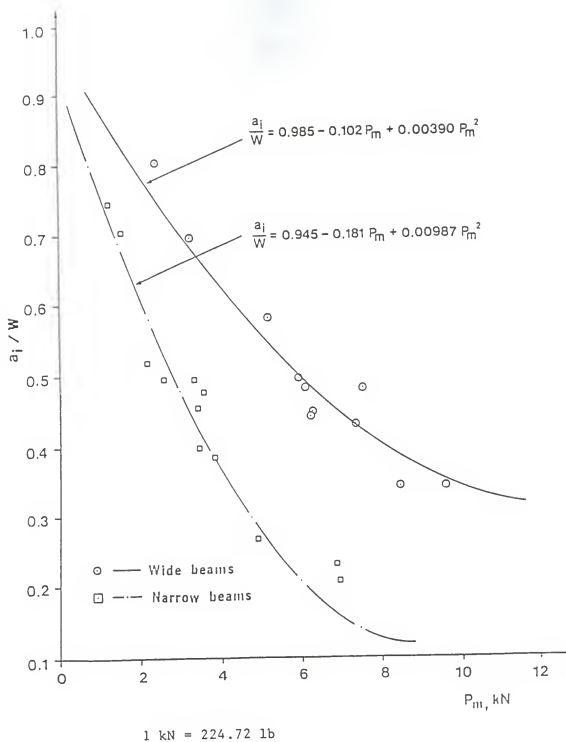
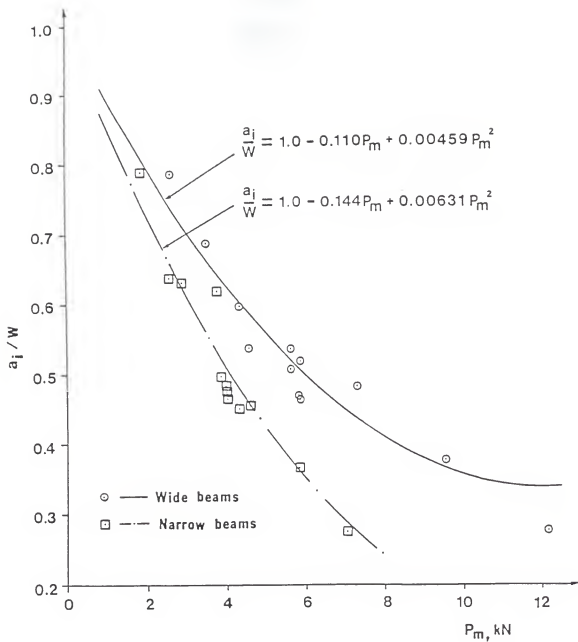


Fig. 3.8 The Maximum Load Calibration Curves for Air-Dried Beams



1 kN = 224.72 lb

Fig. 3.9 The Maximum Load Calibration Curves for Saturated Beams

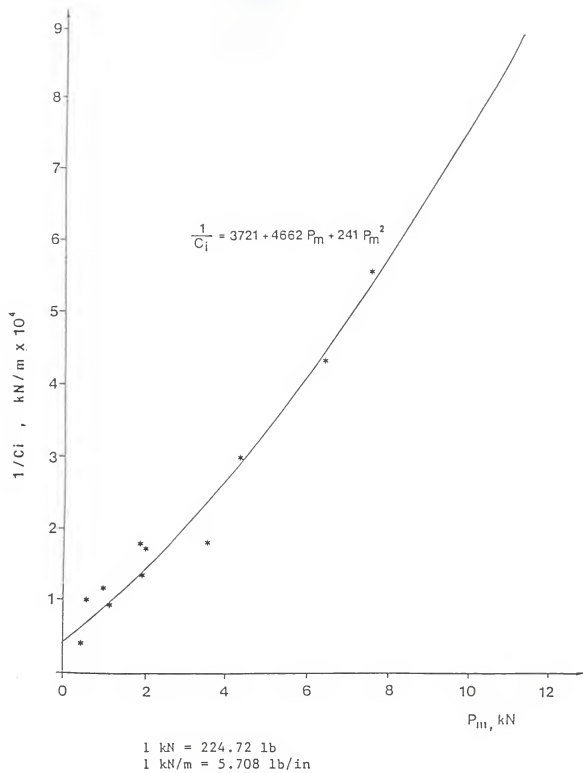


Fig. 3.10 The Compliance Calibration Curve
for Oven-Dried, Narrow Beams

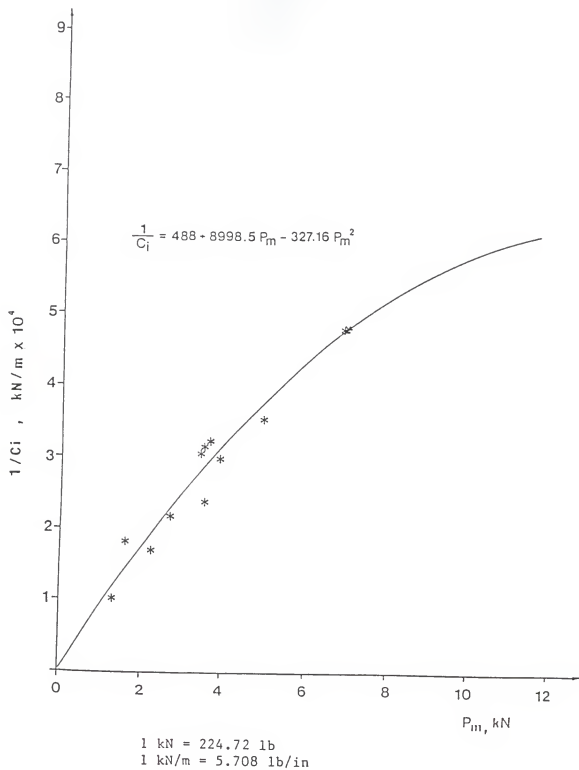


Fig. 3.11 The Compliance Calibration Curve
for Oven-Dried, Wide Beams

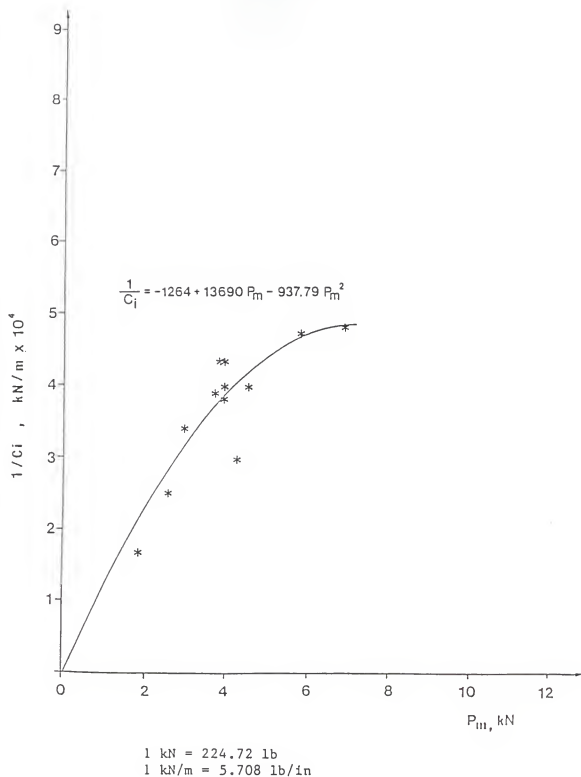
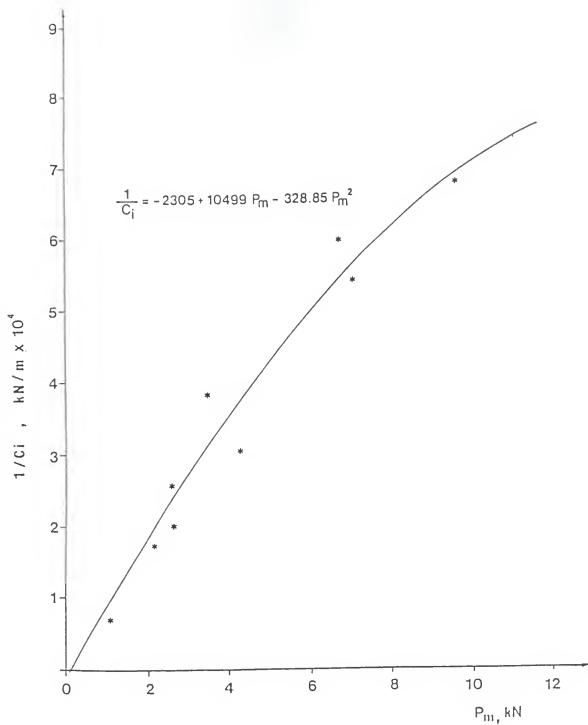
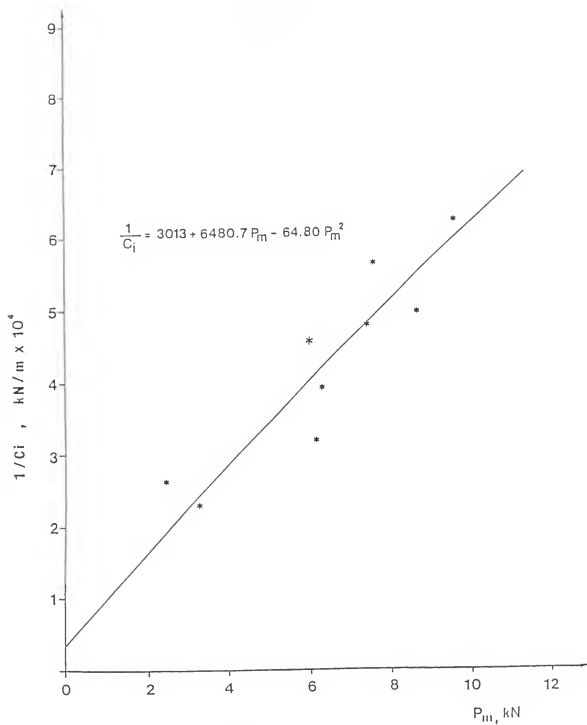


Fig. 3.12 The Compliance Calibration Curve
for Air-Dried, Narrow Beams



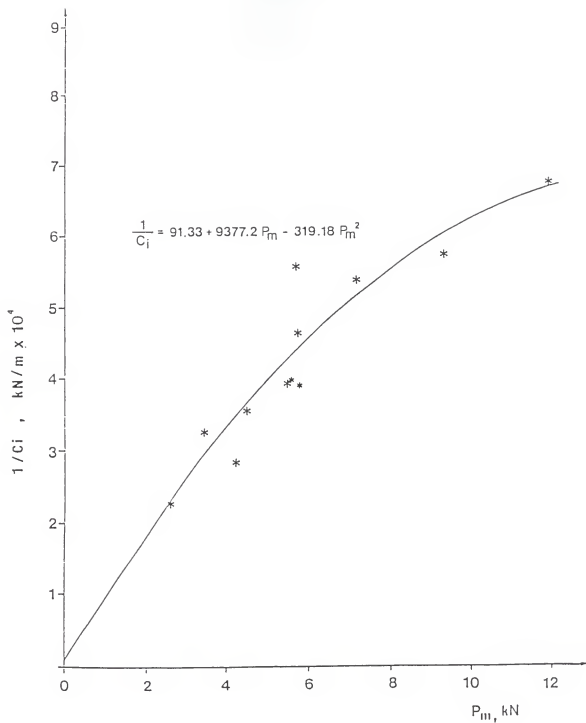
1 kN = 224.72 lb
 1 kN/m = 5.708 lb/in

Fig. 3.13 The Compliance Calibration Curve
 for Air-Dried, Wide Beams



1 kN = 224.72 lb
 1 kN/m = 5.708 lb/in

Fig. 3.14 The Compliance Calibration Curve
 for Saturated, Narrow Beams



1 kN = 224.72 lb
 1 kN/m = 5.708 lb/in

Fig. 3.15 The Compliance Calibration Curve
 for Saturated, Wide Beams

CHAPTER 4

Applied Methods And Experimental Results

4.1 Methods of Calculation for Fracture Toughness

In the past decade, many researchers have conducted numerous experiments to develop approaches for estimating the critical stress intensity factor of cementitious materials such as concrete. Some of those based on LEFM are proposed as standardized testing methods and presented herein along with other methods.

4.1.1 Go/Refai/Swartz (G/R/S) Method (1, 2, 3)

The formula used in this method is based on the bending analogy, and is similar to the Srawley formula (17). The Williams' stress function

$$\begin{aligned} \phi = \sum_{n=1}^N r^{\frac{n+2}{2}} \{ a_n \left[\sin\left(\frac{n}{2} - 1\right) \theta - \frac{n-1}{n+2} \sin\left(\frac{n}{2} + 1\right) \theta \right] \right. \\ \left. + b_n \left[\cos\left(\frac{n}{2} - 1\right) \theta - \cos\left(\frac{n}{2} + 1\right) \theta \right] \right\} \dots (4.1) \end{aligned}$$

was applied to the single-edge-notch beam and evaluated at 23 boundary stations, using the boundary collocation method. The first constant of those obtained by this method a_1 , dominates the equation and is used to evaluate the stress intensity K_I since

$$K_I = - a_1 \sqrt{2\pi} \dots \dots \dots (4.2)$$

Then, through the use of the least squares method to curve-fit the numerical results, K_I could be estimated, using the following equation:

$$K_I = (M/BW^{1.5}) A(z), \quad . \quad . \quad . \quad . \quad (4.3)$$

where $M = P_m S/4$

and, for $S/W = 4$

$$A(Z) = 1.503Z^2 - 6.989Z + 2.630 + 4.835Z^{-1} + 0.207Z^{-2}$$

$$Z = 1 - a/W$$

Coefficients of the function $A(Z)$ for other S/W ratios can be found in Reference (9).

To get the critical stress intensity factor K_{IC} , which is associated with the onset and continuation of unstable crack growth, the crack length must be used at the point of instability which lies on the descending portion of the P-CMOD curve with the value of $0.95P_m$. This crack length is called the effective crack length, a_e , in which the LEFM formula may still be used even when a process zone exists. By means of the maximum load calibration curve or equations given in Figs. 3.7 to 3.9, the effective crack length a_e can be easily found. After that, the value of K_{IC} can be calculated by substituting a_e into Equation (4.3).

Then, using the calculated K_{IC} the energy release rate based upon its LEFM definition can be obtained from the formula as:

$$G_{IC} = K_{IC}^2/E_C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.4)$$

In this, the effect of Poisson's ratio is neglected.

The average values of K_{IC} and G_{IC} for each beam series

with various curing conditions are shown in Tables 4.1 to 4.6, respectively, and a summary considering only $a_e/W \leq 0.65$ (2, 3) is shown in Table 4.7. The effect of the three curing conditions for each beam series on K_{IC} is displayed in Figs. 4.1 and 4.2. Note that for both beam series the fracture toughness, K_{IC} , in air-dried and saturated conditions exhibits invariant values with the crack growth; while for the oven-dried beams a striking trend appears to occur: the K_{IC} values vary with the increase of the crack length. In addition, a plot of average K_{IC} versus moisture content is shown in Fig. 4.3. It is seen that the average values of K_{IC} for oven-dried beams are very low as compared with either those for air-dried or saturated.

4.1.2 Jenq/Shah (J/S) Method (6)

On the basis of LEFM and nonlinear fracture mechanics, a two-parameter model (i.e., $K_{IC}^* = K_{IC}$ and $CTOD_c$) is suggested to characterize the fracture process of concrete. In this study, the critical tip opening displacement, $CTOD_c$ was not determined. The concept behind this model can be explained from the P versus $CMOD$ relationship. Initially, the P - $CMOD$ plot is linear up to about half the maximum load while the corresponding crack tip opening displacement, $CTOD$, is zero. Then, a significant inelastic displacement and slow crack growth occur during which the load increases from $0.5 P_m$ on the ascending part to $0.95 P_m$ on the descending branch. The latter load station defines the

critical point, often called the point of instability, in which the CTOD, as well as K_I , reaches a critical value, i.e., $CTOD = CTOD_C$ and $K_I = K_{IC}$.

To calculate the stress intensity factor, the effective crack length a_e should be determined first. Before using the proposed equation by this method, an initial crack length a_i must be measured experimentally or obtained as a function of Young's Modulus E_t and the initial compliance C_i :

$$E_t = 6S (a_i + HO)(1/C_i) V_1(A)/W^2B, \dots (4.5)$$

in which, HO is the distance from the face of the beam to the knife edge to which the transducer is attached. The term $V_1(A)$ is defined as

$$V_1(A) = 0.76 - 2.28A + 3.87A^2 - 2.04A^3 + 0.66/(1-A)^2. (4.6)$$

$$\text{and } A = a_i / W.$$

Knowing a_i and the unloading compliance C_u at $0.95 P_m$, a trial and error method or numerical iteration scheme can be applied to determine the effective crack length a_e by satisfying the following equation.

$$E_t = 6S (a_e + HO)(1/C_u) V_1(a_e/W) /W^2B \dots (4.7)$$

where E_t is the same as in Equation (4.5).

Herein, the Newton's Method is utilized to obtain the effective crack length a_e . First, equate Equations (4.6) to (4.7) so that the terms of E_t , S , W , B can be canceled out. Then

$$(a_e + HO) V_1\left(\frac{a_e}{W}\right) = \frac{C_u}{C_i} (a_i + HO) V_1(A) \dots (4.8)$$

Since H_0 , C_u and C_i are known, and the initial crack length a_i is experimentally determined, a constant value can be created on the right-hand side of Equation (4.8). Then, after proceeding through an iteration process, the only variable a_e can be obtained.

Once a_e is obtained, the critical stress intensity factor as well as the critical energy release rate are calculated applying Go's formula, i.e., Equations (4.3) and (4.4). The results in Tables 4.8 and 4.9 are for those beams for which unloading data were taken.

4.1.3 The Karihaloo/Nallathambi (K/N) Method (7)

Karihaloo and Nallathambi proposed an analytical expression for determining K_c and G_c of a three-point bend concrete beam. In this method, the extended crack growth is based on the results of a series of tests and a self-consistent approximation to the nonlinear response of slow crack growth prior to fracture. At the growing crack front, the Young's Modulus E_c is reduced and depends not only on the mix variables, but also on the specimen dimensions and geometry. A regression formula based on this concept using a finite element method and various experimental results is used to estimate the extended crack length as follows:

$$(a_e - a)/W = \frac{f_c'}{E_c} \left[\beta_0 + \beta_1 \left(\frac{g}{g+1} \right)^2 + \beta_2 \left(\frac{g}{g+1} \right) \left(\frac{a}{W} \right) + \beta_3 \left(\frac{a}{W} \right) \left(\frac{S}{W} \right) + \beta_4 \left(\frac{W}{W+1} \right) \right] \dots \quad (4.9)$$

where the regression coefficients are

$$\beta_0 = 3960$$

$$\beta_1 = 144$$

$$\beta_2 = -88.2$$

$$\beta_3 = 8.7$$

$$\beta_4 = -3950$$

In Equation (4.9), the crack length $a = a_{oi}$ for precracked beams. The maximum aggregate size, g used herein, is 0.75 in. (19 mm) for all concrete specimens.

After the extended crack length is found, the stress intensity factors and the energy release rate at the tip of an advancing crack can be calculated from the following formulas:

$$K_{IC} = \sigma_0 a_e y_1 (a_e/W) y_2 (a_e/W, S/W) \quad . \quad . \quad . \quad (4.10)$$

$$G_{IC} = (\sigma_0^2 a_e / E_c) z_1 (a_e/W) z_2 (a_e/W, S/W) \quad . \quad . \quad (4.11)$$

$$\sigma_0 = 1.5 \text{ PS/BW}^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.12)$$

The various functions appearing in Equations (4.10) and (4.11) are defined as follows:

$$y_1(a_e/W) = A_0 + A_1 (a_e/W) + A_2 (a_e/W)^2 + A_3 (a_e/W)^3 + A_4 (a_e/W)^4$$

$$y_2(a_e/W, S/W) = B_0 + B_1 (S/W) + B_2 (S/W)^2 + B_3 (S/W)^3 \\ + B_4 (S/W) (a_e/W) + B_5 (S/W)^2 (a_e/W)$$

$$z_1(a_e/W) = C_0 + C_1 (a_e/W) + C_2 (a_e/W)^2 + C_3 (a_e/W)^3 + C_4 (a_e/W)^4$$

$$z_2(a_e/W, S/W) = D_0 + D_1 (S/W) + D_2 (S/W)^2 + D_3 (S/W)^3 \\ + D_4 (S/W) (a_e/W) + D_5 (S/W)^2 (a_e/W)$$

The coefficients A_i , B_i , C_i , D_i are given in the following table.

i	Ai	Bi	Ci	Di
0	3.646	0.4607	1.564	1.9560
1	-6.789	0.0484	-8.32	0.3982
2	39.240	-0.0063	52.95	-0.0553
3	-76.820	0.0003	-124.9	0.0027
4	74.330	-0.0059	122.9	0.0202
5	----	0.0003	----	-0.0055

In order to apply this method to the precracked beams, the initial crack depth was assumed to be outside the process zone, i.e., excluding any microcracking, and was equal to a_{0i} , the distance from the crack "mouth" to the root of the "V-shape" revealed by the dye. The results obtained from several specific beams are shown in Tables 4.10 and 4.11.

4.2 Methods of Calculation for Energy Release Rate

The methods for determining the energy release rate mentioned in Section 4.1 are based on the determined stress intensity using LEFM and represent only the surface energy of separation. Since a process (plastic) zone exists in the fracture of real concrete, these energy release rates determined from the above methods are not representative. Instead of this, some other approaches are proposed to obtain more realistic values of energy release rates. Two of them are presented herein:

4.2.1 J-Integral Method

For a structure of unit thickness under the action of the load P , the load point undergoes a relative displacement v . When the crack increases in size by an amount da , the displacement will increase by an amount dv . Hence, the work done by the external force is Pdv . If the total elastic energy is U_t , then the energy release rate following (18) is

$$G = d(Pv - U_t) / da \quad . \quad . \quad . \quad . \quad . \quad (4.15)$$

Use this concept, a formula was presented by Refai (5).

$$G_{ic} = \frac{1}{1.15BW} \left[\frac{P_i dv}{d(a/W)_i} - \frac{dU_i}{d(a/W)_i} \right] \quad . \quad . \quad . \quad (4.16)$$

In this, the softening portion of the load versus LPD diagram is divided into many segments of the same width (i.e., dv is kept constant) as shown in Fig. 4.7. The width dv is selected depending on the accuracy required. P_i is the average load in the i th interval. The term $d(a/W)_i$ represents the change in crack length versus beam depth in the i th interval; it can be found from the maximum load calibration curve or equation. The change of energy dU_i corresponds to the decrease in elastic energy due to the incremental crack growth at i th stage. It can be estimated by using the unloading slope which may be obtained from the curve or equation of maximum load versus compliance to measure the difference in triangular areas corresponding to the changes in the elastic energy.

This was done only for several selected beams which had nice traces in the P -LPD plots. The results from typical beams for each group are plotted in Fig. 4.8 to 4.10.

4.3 Summary of the experimental results

1. From the tables for 3 in. and 6 in. beams, and neglecting the beams with $a_e/W > 0.65$, the average values of K_{IC} for air-dried beams are $803 \text{ lb-in}^{-3/2}$ ($883 \text{ kN-m}^{-3/2}$) with C.V.= 2.8% and $876 \text{ lb-in}^{-3/2}$ ($961 \text{ kN-m}^{-3/2}$) with C.V.= 2.0%, respectively, which shows no significant difference between them. Similar results for saturated beams with 3 in. and 6 in. wide are $1180 \text{ lb-in}^{-3/2}$ ($1300 \text{ kN-m}^{-3/2}$) with C.V.= 2.1% and $860 \text{ lb-in}^{-3/2}$ ($956 \text{ kN-m}^{-3/2}$) with C.V.= 7.3%, which implies a side (width) effect on them. In oven-dried condition, the average K_{IC} values are $559 \text{ lb-in}^{-3/2}$ ($615 \text{ kN-m}^{-3/2}$) with C.V.= 36.2% for 3 in. wide beams and $361 \text{ lb-in}^{-3/2}$ ($397 \text{ kN-m}^{-3/2}$) with C.V.= 32.9% for 6 in. wide beams. It is noted that the coefficients of variance for both the 3 in. and 6 in. wide oven-dried beams are very high compared to those in the air-dried and saturated conditions so that the average values for oven-dried beams are meaningless.

2. Results of the determination of K_{IC} from the J/S method and the K/N method based on some specific beams and compared with the G/R/S method are summarized in Table 4.12. It is seen that the results obtained from the G/R/S method and the J/S method seem to be more consistent in value; while the K/N method turn out higher values than those from the previous methods. However, basically, the results from the three methods are in agreement.

3. The energy release rate J_{IC} as determined from the plots for both the 3 in. and 6 in. wide beams are

respectively, 0.274 lb/in (47.9 N/m) and 0.184 lb/in (32.2 N/m) in the oven-dried condition; 0.222 lb/in (38.9 N/m) and 0.239 lb/in (41.9 N/m) in the air-dried condition; 0.268 lb/in (47.0 N/m) and 0.285 lb/in (49.9 N/m) in the saturated condition. These values are higher than those of the average G_{IC} based on calculated K_{IC} by the Go/ Refai/Swartz method as given in Table 4.7.

4. Each point in Fig 4.8 to 4.10 denotes the corresponding G_{IC} value to each ith segment of any typical beam, selected from a certain group. To some extent, G_{IC} is constant with an average of 0.261 lb/in (45.7 N/m) for air-dried, narrow beam D23; the others display a striking trend, and it is not meaningful to find average values.

Table 4.1 K_{IC} Data by G/R/S Method for Oven-Dried Narrow Beams

No.	a_i/W	a_i/W^*	a_e/W^*	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
D1	0.195	0.205	0.210	1720 765	912 1003	0.175 30.61
D2	0.219	0.223	0.230	1460 650	820 902	0.141 24.77
D3	0.273	0.283	0.292	980 436	656 721	0.090 15.82
D4	0.367	0.320	0.329	800 356	592 651	0.074 12.91
D5	0.381	0.445	0.455	430 191	448 492	0.042 7.38
D6	0.539	0.555	0.560	255 113	358 393	0.027 4.71
D7	0.602	0.580	0.590	220 98	338 372	0.024 4.21
D8	0.660	0.670	0.675	135 60	276 304	0.016 2.81
D9	0.766	0.720	0.735	100 45	260 286	0.014 2.49
D10						
D11	0.518	0.450	0.459	420 187	442 486	0.041 7.20
D12	0.489	0.435	0.457	445 198	466 512	0.046 7.99
				Avg.	506 557	0.063 10.99
				C.V.	40.7%	80.6%

* Value from the fitting curve.

Table 4.2 K_{IC} Data by G/R/S Method for Air-Dried Narrow Beams

No.	a_i/W	a_i/W^*	a_e/W^*	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
D13	0.208	0.160	0.175	1600 712	764 840	0.101 17.66
D14	0.269	0.288	0.307	1130 503	788 867	0.107 18.78
D15	0.743	0.722	0.732	300 134	770 847	0.102 17.96
D16	0.497	0.521	0.542	615 274	818 900	0.116 20.25
D17	0.399	0.423	0.442	810 360	814 895	0.114 20.05
D18	0.703	0.679	0.690	365 162	790 869	0.108 18.87
D19	0.234	0.164	0.179	1580 703	764 840	0.101 17.65
D20	0.520	0.588	0.604	510 227	819 901	0.116 20.30
D21	0.385	0.382	0.407	890 396	814 895	0.114 20.03
D22	0.456	0.427	0.448	800 356	817 899	0.115 20.21
D23	0.497	0.438	0.458	780 347	819 901	0.116 20.29
D24	0.478	0.410	0.431	835 372	814 896	0.115 20.07
				Avg.	799 879	0.110 19.34
				C.V.	2.72%	5.40%

* Value from the fitting curve.

Table 4.3 K_{IC} Data by G/R/S Method for Saturated Narrow Beams

No.	a_i/W	a_i/W^*	a_e/W^*	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
D25	0.273	0.293	0.315	1580 703	1126 1239	0.228 39.95
D26	0.636	0.665	0.679	580 258	1204 1324	0.261 45.67
D27	0.457	0.468	0.487	1030 458	1172 1289	0.247 43.25
D28	0.788	0.748	0.758	420 187	1215 1336	0.265 46.49
D29	0.630	0.628	0.644	660 294	1209 1330	0.263 46.08
D30	0.366	0.366	0.386	1325 590	1144 1259	0.236 41.27
D31	0.618	0.542	0.558	850 378	1185 1304	0.253 44.27
D32	0.451	0.490	0.509	970 432	1174 1291	0.248 43.40
D33	0.475	0.521	0.540	900 401	1190 1309	0.255 44.64
D34	0.494	0.530	0.550	874 389	1190 1309	0.255 44.64
D35	0.464	0.521	0.540	900 401	1190 1309	0.255 44.64
D36	0.483	0.521	0.540	900 401	1190 1309	0.255 44.64
				Avg.	1183 1301	0.252 44.08
				C.V.	2.09%	4.10%

* Value From the fitting curve.

Table 4.4 K_{IC} Data by G/R/S Method for Oven-Dried Wide Beams

No.	a_i/W	a_i/W^*	a_e/W^*	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
E1	0.204	0.208	0.214	2200 979	590 649	0.073 12.81
E2	0.291	0.258	0.258	1550 690	472 519	0.047 8.19
E3	0.258	0.245	0.252	1620 721	485 533	0.049 8.65
E4	0.291	0.330	0.340	980 436	374 411	0.029 5.14
E5	0.391	0.375	0.385	780 347	336 370	0.024 4.15
E6	0.499	0.540	0.550	360 160	245 270	0.013 2.21
E7	0.432	0.465	0.475	500 223	275 303	0.016 2.78
E8	0.647	0.625	0.640	255 113	230 253	0.011 1.95
E9	0.397	0.428	0.437	610 271	302 333	0.019 3.37
E10						
E11						
E12	0.342	0.430	0.440	600 267	300 330	0.019 3.31
				Avg.	361 397	0.030 5.26
				C.V.	31.1%	63.5%

* Value from the fitting curve.

Table 4.5 K_{IC} Data by G/R/S Method for Air-Dried Wide Beams

No.	a_i/W	a_i/W^*	a_e/W^*	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
E13	0.345	0.391	0.406	1950 868	889 978	0.136 23.90
E14	0.444	0.489	0.505	1440 641	861 947	0.128 22.45
E15	0.698	0.685	0.696	760 338	841 925	0.122 21.42
E16	0.585	0.549	0.566	1200 534	857 943	0.127 22.22
E17	0.345	0.356	0.371	2200 979	912 1004	0.144 25.19
E18	0.500	0.503	0.523	1375 612	866 952	0.129 22.68
E19	0.805	0.750	0.761	570 254	836 920	0.121 21.16
E20	0.487	0.427	0.443	1740 774	877 964	0.133 23.26
E21	0.439	0.436	0.452	1700 757	878 966	0.133 23.32
E22	0.450	0.487	0.502	1450 645	860 946	0.128 22.38
E23	0.485	0.493	0.511	1420 632	864 950	0.129 22.58
E24						
				Avg.	867 954	0.130 22.78
				C.V.	2.35%	4.72%

* Value from the fitting curve.

Table 4.6 K_{IC} Data by G/R/S Method for Saturated Wide Beams

No.	a_i/W	a_i/W^*	a_e/W^*	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
E25	0.373	0.364	0.375	2140 950	897 987	0.140 24.53
E26	0.536	0.589	0.605	1025 456	826 908	0.123 21.48
E27	0.684	0.663	0.676	790 352	811 892	0.118 20.72
E28	0.482	0.435	0.450	1650 754	847 932	0.129 22.63
E29	0.509	0.524	0.537	1270 565	833 916	0.125 21.84
E30	0.594	0.607	0.623	970 432	828 911	0.123 21.61
E31	0.786	0.735	0.748	595 265	821 903	0.121 21.23
E32	0.277	0.335	0.336	2725 1213	1028 1131	0.190 33.31
E33	0.534	0.520	0.537	1270 565	833 916	0.125 21.84
E34	0.467	0.510	0.527	1310 583	834 918	0.125 21.93
E35	0.465	0.508	0.525	1320 587	836 919	0.126 22.01
E36	0.516	0.508	0.525	1320 587	836 919	0.126 22.01
				Avg.	852	0.131
					938	22.93
				C.V.	6.64%	14.2%

* Value from the fitting curve.

Table 4.7 Average Value of Fracture Parameters

Curing Condition	Size Group No.	K_{IC}^1 lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC}^2 lb/in N/m	a_e/W Range
Oven-Dried	B = 3 in. D1-D12	559 615	0.0656 11.5	0.210-0.590
		C.V. = 36.2 %	N = 9	
	B = 6 in. E1-E12	361 397	0.0274 4.8	0.214-0.640
		C.V. = 32.9 %	N = 10	
Air-Dried	B = 3 in. D13-D24	803 883	0.111 19.4	0.175-0.604
		C.V. = 2.8 %	N = 10	
	B = 6 in. E13-E24	874 961	0.250 23.1	0.371-0.511
		C.V. = 2.0 %	N = 9	
Saturated	B = 3 in. D25-D36	1180 1300	0.250 43.8	0.315-0.644
		C.V. = 2.1 %	N = 11	
	B = 6 in. E25-E36	860 946	0.133 23.3	0.336-0.623
		C.V. = 7.3 %	N = 10	

1. K_{IC} determined by Go/Refai/Swartz method (1, 2, 3), and $a_e/W \leq 0.65$.
2. $G_{IC} = K_{IC}^2 / E_C$.
3. The C.V. values calculated only for K_{IC} data.

Table 4.8 K_{IC} Data by Jenq/Shah Method (6) for Narrow Beams

No.	a_i/W	a_e/W	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
(Oven Dried)					
D11	0.518	0.594	420	654	0.090
			1.87	719	15.72
D12	0.489	0.531	445	573	0.069
			1.98	631	12.10
			Avg.	613	0.079
				675	13.91
(Air Dried)					
D21	0.385	0.422	890	847	0.124
			3.96	932	21.72
D22	0.456	0.478	800	888	0.136
			3.56	976	23.83
D23	0.497	0.550	780	1063	0.195
			3.47	1168	34.14
D24	0.478	0.539	835	1101	0.209
			3.72	1211	36.69
			Avg.	975	0.166
				1072	29.10
(Saturated)					
D33	0.475	0.527	900	1146	0.236
			4.01	1261	41.41
D34	0.494	0.517	874	1082	0.210
			3.89	1190	36.88
D35	0.464	0.498	900	1056	0.200
			4.01	1161	35.12
D36	0.483	0.510	900	1092	0.214
			4.01	1201	37.58
			Avg.	1094	0.215
				1203	37.74

Table 4.9 K_{IC} Data by Jenq/Shah Method (6) for Wide Beams

No.	a_i/W	a_e/W	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
(Oven Dried)					
E9	0.397	0.439	610	304	0.019
			2.71	334	3.40
E12	0.342	0.383	600	257	0.014
			2.67	283	2.43
			Avg.	281	0.017
				309	2.92
(Air Dried)					
E21	0.439	0.478	1700	943	0.154
			7.57	1037	26.91
E22	0.450	0.492	1450	836	0.121
			6.45	920	21.16
E23	0.485	0.533	1420	920	0.146
			6.32	1012	25.62
			Avg.	900	0.140
				990	24.56
(Saturated)					
E33	0.534	0.567	1270	910	0.149
			5.65	1001	26.08
E34	0.467	0.500	1310	773	0.107
			5.83	850	18.81
E35	0.465	0.506	1320	792	0.113
			5.87	871	19.76
E36	0.516	0.541	1320	875	0.138
			5.87	963	24.15
			Avg.	837	0.127
				921	22.20

Table 4.10 K_{IC} Data by Karihaloo/Nallathambi Method (7) for Narrow Beams

No.	a_{oi}/W	a_e/W	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
(Oven Dried)					
D11	0.293	0.538	420	688	0.092
			1.87	757	16.12
D12	0.238	0.487	445	614	0.074
			1.98	675	12.89
			Avg.	651	0.083
				716	14.51
(Air Dried)					
D21	0.231	0.476	890	1182	0.224
			3.96	1300	39.32
D22	0.281	0.521	800	1237	0.245
			3.56	1361	42.92
D23	0.269	0.510	780	1161	0.216
			3.47	1277	37.88
D24	0.281	0.521	835	1291	0.267
			3.72	1420	46.77
			Avg.	1218	0.238
				1340	41.72
(Saturated)					
D33	0.294	0.516	900	1365	0.311
			4.01	1501	54.44
D34	0.280	0.503	874	1269	0.269
			3.89	1395	47.09
D35	0.279	0.502	900	1302	0.283
			4.01	1432	49.63
D36	0.248	0.473	900	1187	0.236
			4.01	1305	41.28
			Avg.	1281	0.275
				1409	48.11

Table 4.11 K_{IC} Data by Karihaloo/Nallathambi Method (7) for Wide Beams

No.	a_{oi}/W	a_e/W	P_m lb kN	K_{IC} lb-in ^{-3/2} kN-m ^{-3/2}	G_{IC} lb/in N/m
(Oven Dried)					
E9	0.250	0.498	610 2.71	436 480	0.037 6.51
E12	0.175	0.430	600 2.67 Avg.	346 381 391 430	0.024 4.13 0.030 5.32
(Air Dried)					
E21	0.313	0.551	1700 7.57	1459 1605	0.340 59.49
E22	0.288	0.528	1450 6.45	1146 1260	0.210 36.79
E23	0.363	0.597	1420 6.32 Avg.	1453 1598 1353 1488	0.331 58.02 0.294 51.45
(Saturated)					
E33	0.363	0.580	1270 5.65	1215 1336	0.243 42.56
E34	0.295	0.517	1310 5.83	996 1096	0.166 29.02
E35	0.295	0.517	1320 5.87	1004 1104	0.168 29.46
E36	0.355	0.572	1320 5.87 Avg.	1227 1350 1111 1221	0.249 43.56 0.206 36.15

Table 4.12 Average Values of Fracture Toughness Using Three Methods

Curing Condition	Beam Nos.	K_{IC} , $\text{lb-in}^{-3/2}$ $\text{kN-m}^{-3/2}$		
		G/R/S ¹	J/S ²	K/N ³
Oven-Dried	D11, D12	454	613	651
		499	674	716
	E9, E12	300	270	391
		330	297	430
Air-dried	D21, D22,	816	975	1218
	D23, D24	898	1072	1340
	E21, E22,	867	855	1353
	E23	954	940	1488
Saturated	D33, D34,	1190	1094	1281
	D35, D36	1309	1203	1409
	E33, E34,	835	796	1110
	E35, E36	918	876	1221

1. Method of Go, Refai, Swartz (1, 2, 3)

2. Method of Jenq, Shah (6)

3. Method of Karihaloo, Nallathambi (7)

Table 4.13 J_{IC} Values for Narrow Beams (2, 4)

No.	a_i/W	U, lb-in	
(Oven-dried)			
D1	0.195	4.65	
D2	0.219	3.63	
D3	0.273	3.16	
D4	0.367	3.11	
D5	0.381	1.51	
D6	0.539	0.89	
D7	0.602	0.52	
D8	0.660	0.31	$N = 11$
D9	0.766	0.32	$Y = -7.55 X + 5.34$
D11	0.518	1.35	$COR = -0.938$
D12	0.489	1.44	$J_{IC} = 0.274 \text{ lb/in}$ (48.0 N/m)
(Air-dried)			
D13	0.208	2.26	
D14	0.269	3.83	
D15	0.743	0.45	
D16	0.497	1.83	
D17	0.399	2.71	
D18	0.703	0.86	
D19	0.234	4.90	
D20	0.520	1.68	
D21	0.385	2.78	$N = 12$
D22	0.456	2.14	$Y = -6.12 X + 5.06$
D23	0.497	2.03	$COR = -0.853$
D24	0.478	2.30	$J_{IC} = 0.222 \text{ lb/in}$ (38.9 N/m)
(Saturated)			
D25	0.273	5.00	
D26	0.636	1.50	
D27	0.457	2.71	
D28	0.788	0.99	
D29	0.630	1.35	
D30	0.366	4.05	
D31	0.618	1.94	
D32	0.451	2.91	
D33	0.475	1.89	$N = 12$
D34	0.494	1.88	$Y = -7.4 X + 6.15$
D35	0.464	2.01	$COR = -0.878$
D36	0.483	2.15	$J_{IC} = 0.268 \text{ lb/in}$ (47.0 N/m)

Note: U = area under P-LPD from 0 to 0.95 P_m on the descending branch.

1 lb-in = 0.113 N-m

Table 4.14 J_{IC} Values for Wide Beams (2, 4)

No.	a_i/W	U, lb-in	
(Oven-dried)			
E1	0.204	7.03	
E2	0.291	4.90	
E3	0.258	4.60	
E4	0.291	3.26	
E5	0.391	1.81	
E7	0.432	1.52	N = 9
E8	0.647	2.07	Y = -10.16 X + 6.86
E9	0.397	1.95	COR = -0.681
E12	0.342	1.54	$J_{IC} = 0.184 \text{ lb/in}$ (32.2 N/m)
(Air-dried)			
E13	0.345	6.98	
E14	0.444	5.83	
E17	0.345	7.98	
E18	0.500	3.92	
E19	0.805	1.38	
E20	0.487	5.42	N = 9
E21	0.439	6.14	Y = -13.17 X + 11.73
E22	0.450	5.05	COR = -0.934
E23	0.485	6.26	$J_{IC} = 0.239 \text{ lb/in}$ (41.9 N/m)
(Saturated)			
E25	0.373	7.41	
E26	0.536	2.97	
E27	0.684	2.15	
E28	0.482	4.92	
E29	0.509	4.12	
E30	0.594	2.79	
E31	0.786	1.79	
E32	0.277	10.40	
E33	0.534	3.82	N = 12
E34	0.467	3.07	Y = -15.75 X + 12.44
E35	0.465	3.59	COR = -0.858
E36	0.516	4.30	$J_{IC} = 0.285 \text{ lb/in}$ (49.9 N/m)

Note: U = area under P-LPD from 0 to the 0.95 P_m on the descending branch.

1 lb-in = 0.113 N-m

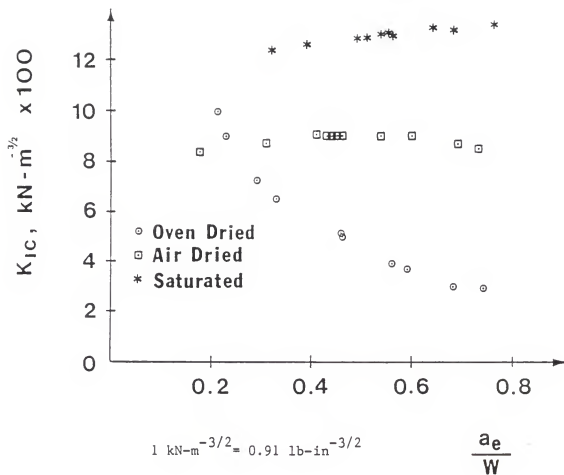


Fig. 4.1 K_{IC} vs. $\frac{a_e}{W}$ for Narrow Beams, G/R/S Method

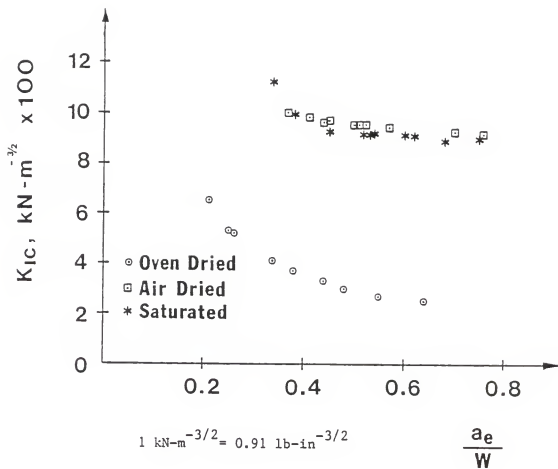
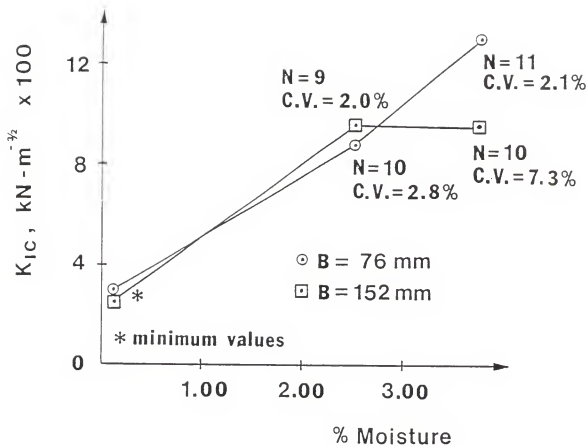


Fig. 4.2 K_{IC} vs. $\frac{a_e}{W}$ for Wide Beams, G/R/S Method



$$1 \text{ kN-m}^{-3/2} = 0.91 \text{ lb-in}^{-3/2}$$

Fig. 4.3 K_{IC} vs. Moisture, G/R/S Method

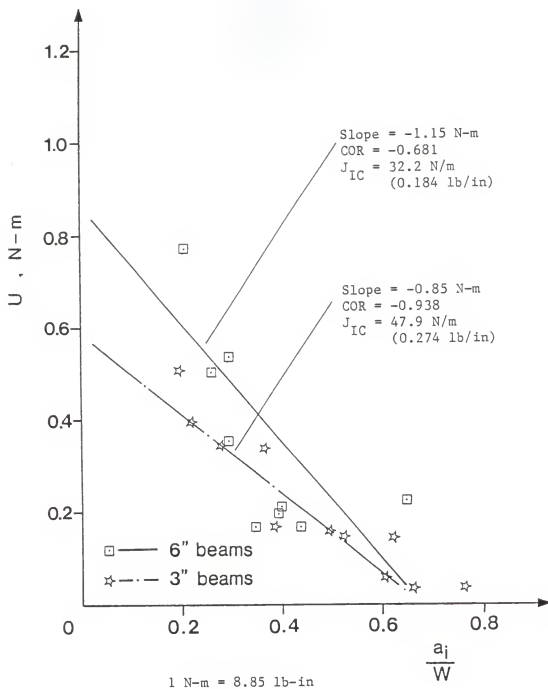


Fig. 4.4 U vs. $\frac{a_i}{W}$ for Oven-Dried Beams,
 J-Integral Method

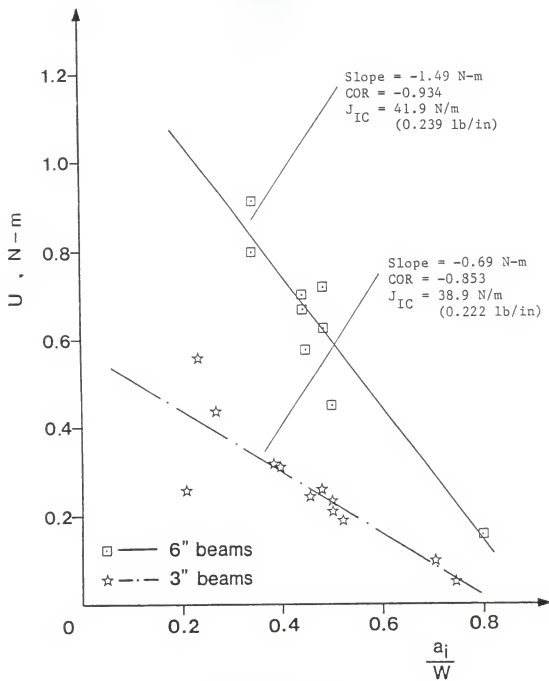


Fig. 4.5 U vs. $\frac{a_i}{W}$ for Air-Dried Beams,
 J-Integral Method

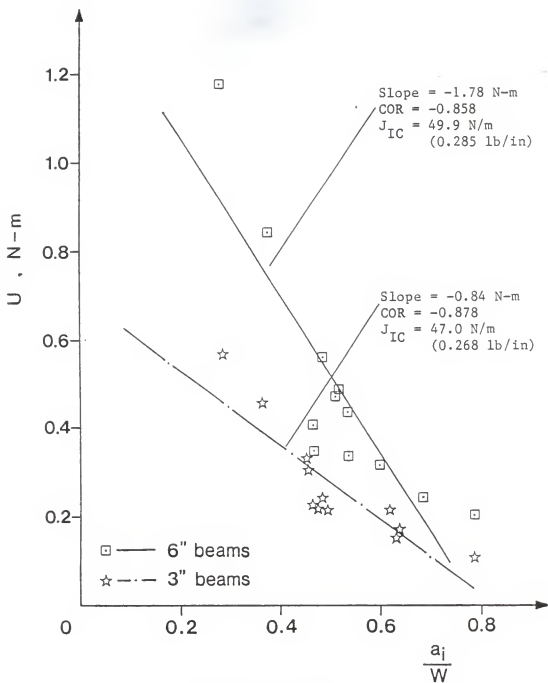


Fig. 4.6 U vs. $\frac{a_i}{W}$ for Saturated Beams,
J-Integral Method

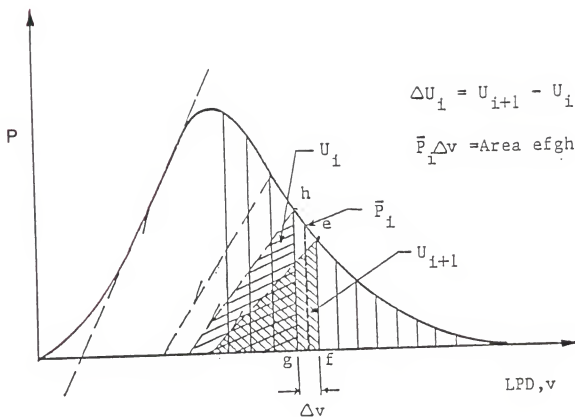


Fig. 4.7 P vs. LPD for The Energy Release Method (2)

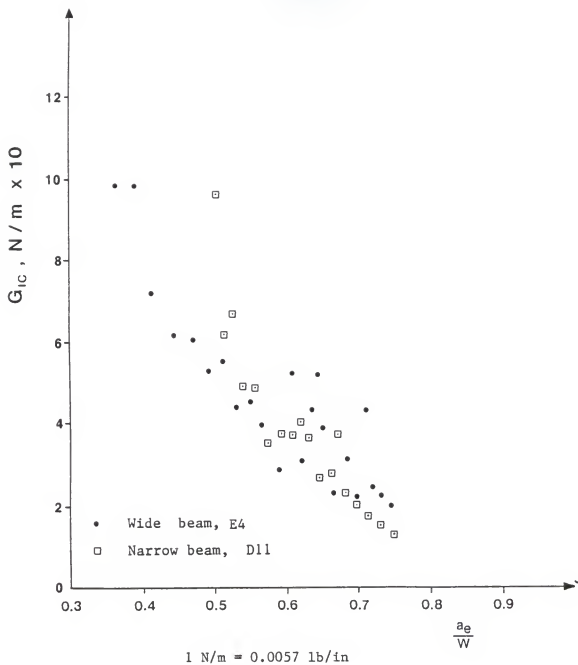


Fig. 4.8 G_{IC} vs. $\frac{a_e}{W}$ for Oven-Dried Beams

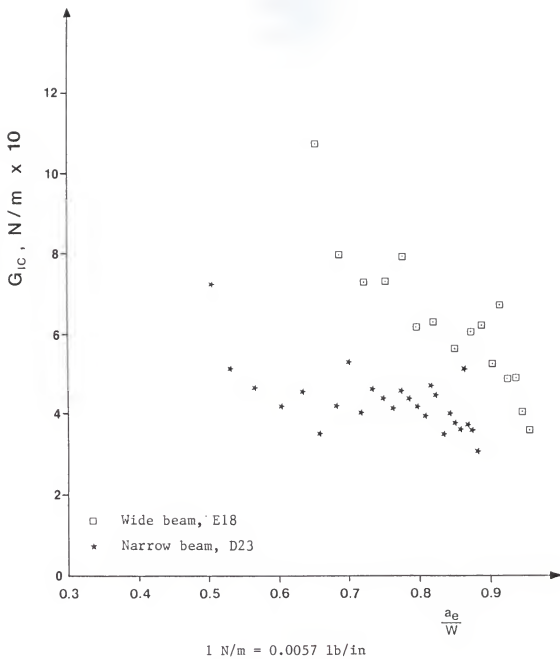


Fig. 4.9 G_{IC} vs. $\frac{a_e}{W}$ for Air-Dried Beams

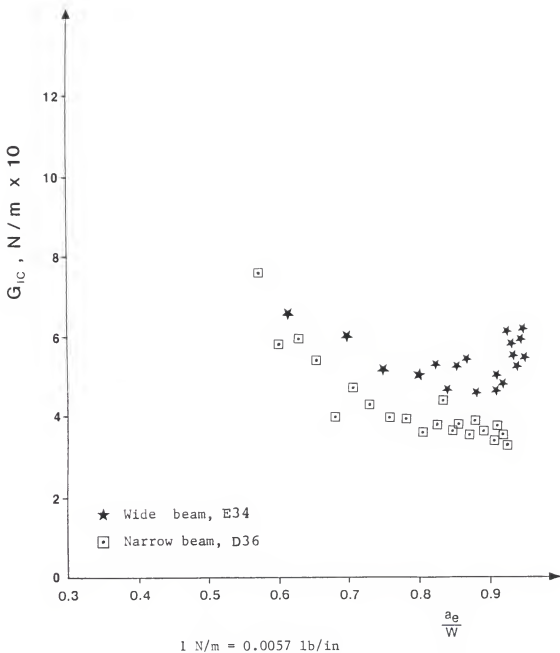


Fig.4.10 G_{IC} vs. a_e/W for Saturated Beams

CHAPTER 5

Conclusions

From the experimental results of this study, in which the influences of curing conditions and size (width) on fracture toughness values as well as energy release rates for concrete beams in three point bending were determined, the following may be concluded:

1. Oven-dried beams exhibit a size effect, but more importantly the fracture toughness K_{IC} decreases with the crack growth. The minimum value of K_{IC} is much lower than the average values for air-dried or saturated beams.
2. For the saturated beams a modest size (width) effect exists. The importance of this is open to question since most concrete structures do not exist in a saturated environment.
3. For the narrow beams a difference in results is obtained between those air-dried and those saturated. The K_{IC} values are higher for saturated beams; however, for wide beams there is no statistically-meaningful difference in results between air-dried and saturated. It seems reasonable that if a curing effect exists it would be more pronounced for the narrow beams since the region of the "side lips" occupies a greater proportion of the total area than is the case for the wide beams.
4. In general, the results obtained from the three methods used to determine K_{IC} are in agreement.
5. The values of energy release rates determined by the

J-Integral method are larger than those by fracture toughness method. This may be because of the existence of the process (plastic) zone, which consumes part of the energy, so that the explanation of the fracture on concrete using only LEFM is not sufficient.

6. From the plots of G_{IC} using the energy release method, very comparable results with those from the Go/Refai/Swartz method can be observed. For the oven-dried beams, G_{IC} varies as the crack grows, just like the trend of K_{IC} versus the crack growth shown previously. For the air-dried beams the size effect is clear. It displays a moderately invariant value for the narrow beam; while for the wide beam the G_{IC} values decrease with the increase of the crack length. For saturated beams, by selecting an appropriate range, the G_{IC} could be treated as an invariant value for both narrow and wide beams; however, size effect still exists.

APPENDIX I

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APPENDIX II

LOAD VERSUS CMOD AND LPD DIAGRAMS FOR
TYPICAL THREE-POINT BENDING SPECIMENS

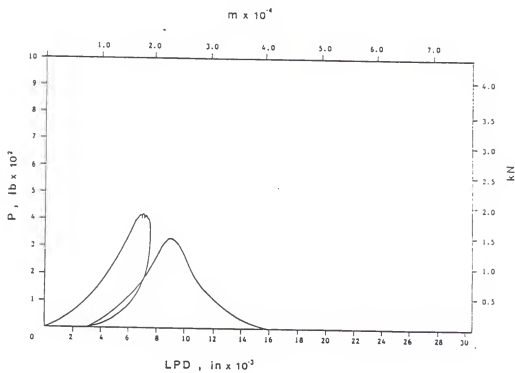
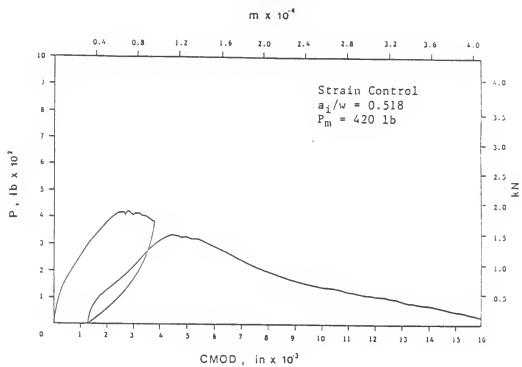


Fig. 1 Load vs. CMOD and LPD for D11,
 Oven-Dried, Narrow Beam

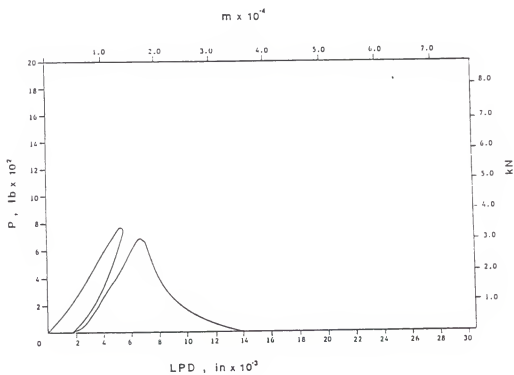
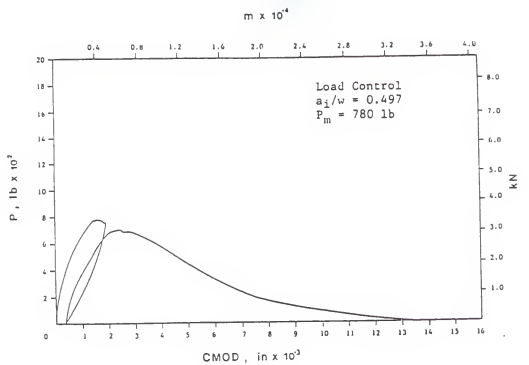


Fig. 2 Load vs. CMOD and LPD for D23,
 Air-Dried, Narrow Beam

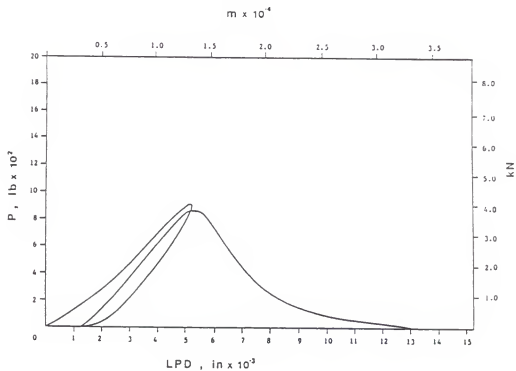
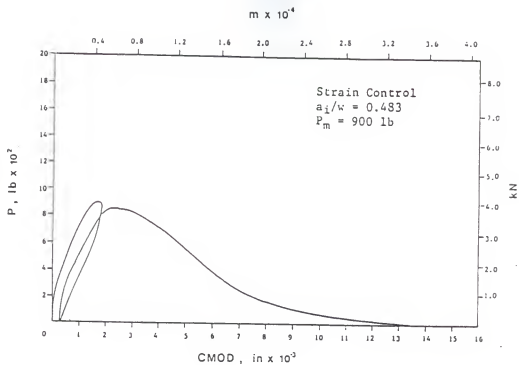


Fig. 3 Load vs. CMOD and LPD for D36,
 Saturated, Narrow Beam

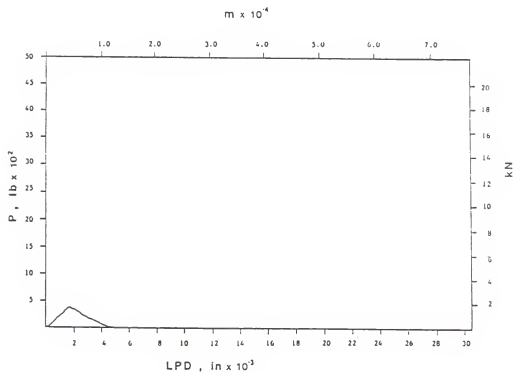
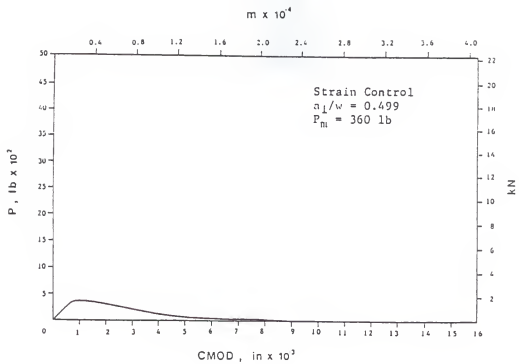


Fig. 4 Load vs. CMOD and LPD for E6,
 Oven-Dried, Wide Beam

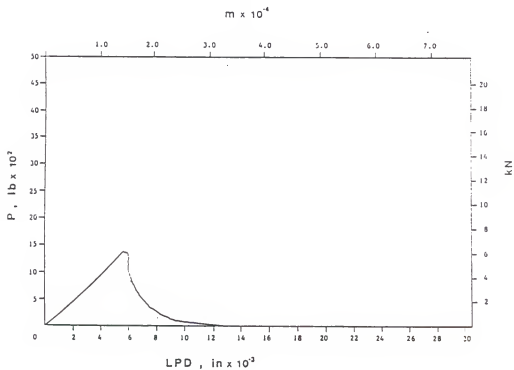
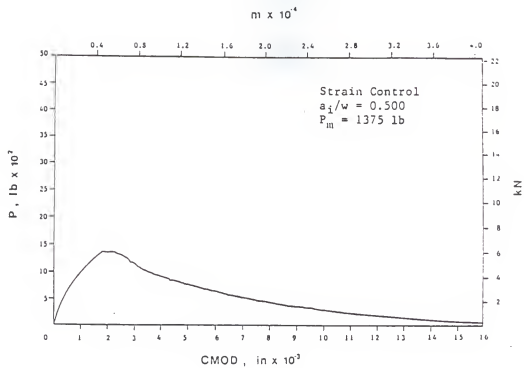


Fig. 5 Load vs. CMOD and LPD for E18,
 Air-Dried, Wide Beam

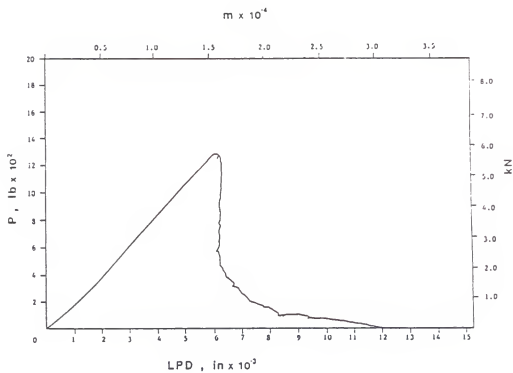
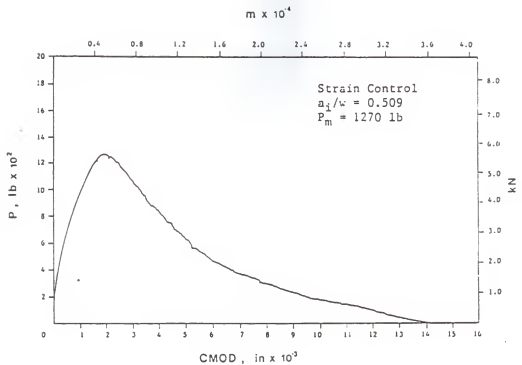


Fig. 6 Load vs. CMOD and LPD for E29,
 Saturated, Wide Beam

INFLUENCE OF CURING CONDITIONS AND WIDTH
ON THE FRACTURE OF CONCRETE BEAMS

by

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B.S.. Chung-Hsing University, Taiwan, 1985

AN ABSTRACT OF A MASTER'S THESIS
submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

Department of Civil Engineering
Kansas State University
Manhattan, Kansas

1989

ABSTRACT

Although a large amount of research has been reported in the literature dealing with curing conditions on the subsequent strength of concrete, few studies have been conducted relating these effects to the fracture properties of concrete, such as fracture toughness and the critical energy release rate. Most of the fracture mechanics tests were done using either saturated or air-dried specimens.

Thirty six beams in two series of 3x8x34 in. and 6x8x34 in. with S/W of 4 were utilized in this experimental program based on the three-point bend tests. The curing conditions were: 1 day in the mold, 30 days in a 100% humidity curing room for all specimens and then for each beam series

- a. 12 beams, 60 days in an oven at 177°F,
- b. 12 beams, 60 days in the laboratory environment,
- c. 12 beams, 60 additional in the curing room.

All beams were precracked and a dye technique was applied. Through the use of three proposed methods, based on LEFM, the fracture toughness and energy release rate could be calculated. As a result, the fracture toughness evaluated by the three methods was found to be independent of the crack length and approximately independent of beam width and curing condition for the air-dried and saturated beams but not for the oven-dried beams. In addition, two other methods for determining the energy release rates were also used to compare with the above results.